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Derek M. Heeren
University of Nebraska-Lincoln, derek.heeren@unl.edu

Todd P. Trooien
South Dakota State University, todd.trooien@sdstate.edu

Hal D. Werner
South Dakota State University

Norman L. Klocke
Kansas State University, Garden City, KS, nklocke@ksu.edu

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ABSTRACT. *Competition for water is increasing while a growing world population requires more food production. It is critical to develop and implement efficient deficit irrigation strategies and to predict the impacts of deficit irrigation on yield. South Dakota State University (SDSU) Management Software, which simulates evapotranspiration and soil water contents, was originally designed as an on-farm decision support system capable of fully automating center pivot irrigation. A simple yield model was developed for the software in order to extend its use for evaluating deficit irrigation strategies. Yield ratio (i.e., actual yield/potential yield) was predicted based on a normalized transpiration ratio (i.e., seasonal transpiration normalized with daily reference evapotranspiration/normalized potential transpiration), requiring only daily transpiration data. Results from the updated software compared favorably with field data for corn under deficit irrigation, indicating that the yield model accounts for yield reductions due to water stress. SDSU Management Software was used to simulate center pivot irrigation and corn yield at seven locations across the Great Plains with historical weather data. Thirty irrigation strategies were evaluated across three soil water holding capacities and three pumping rates. Strategies with high water use efficiencies performed well across all treatments and locations. The recommended maximum yield strategy is 30-60-30 (strategies were defined by the minimum available soil water (%) for early, middle, and late season), which used 4% to 14% less irrigation water than a traditional strategy with negligible or positive impacts on yield. Recommended limited water supply strategies are 15-50-0, 0-30-0, and 0-15-0 for minimal, moderate, and severe water restrictions, respectively. Annual variation in yield was greatest when water was most limited. Reduced pumping rates substantially limited maximum yields for arid locations.*

Keywords. *Deficit irrigation, Corn, Center pivot irrigation, Irrigation modeling, Irrigation management, Water conservation, Yield modeling.*

A growing world population, requiring more drinking water, food production, and industry, results in increasing competition for water. One study predicts that in the year 2050, there will be a worldwide annual water shortage of 640 billion cubic meters (Spears, 2003). Some irrigators are already faced with limited water supplies where their irrigation cannot provide full crop needs, particularly in years with below average precipitation. Drought in western South Dakota has reduced water supplies from several irrigation projects, and low water flows in the Missouri River have restricted irrigation from the reservoirs in the system. Since irrigation is the largest consumptive use of water in many places, accounting for 65% of the fresh water use in the 22 western states (calculated from USGS, 2000), proper irrigation water management is critical to make the best use of the water available.

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The authors are **Derek M. Heeren, ASABE Member Engineer,** Research Engineer, PhD Student, Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma; **Todd P. Trooien,** Professor, **Hal D. Werner, ASABE Member Engineer,** Professor Emeritus, Department of Agricultural and Biosystems Engineering, South Dakota State University, Brookings, South Dakota; and **Norman L. Klocke, ASABE Member Engineer,** Professor, Southwest Research Center, Kansas State University, Garden City, Kansas. **Corresponding author:** Todd P. Trooien, Department of Agricultural and Biosystems Engineering, 215 Agricultural Engineering, Box 2120, South Dakota State University, Brookings, SD 57007; phone: 605-688-5677; e-mail: todd.trooien@sdstate.edu.

As competition for irrigation water supplies becomes greater, it will be necessary for irrigators to optimize the use of available water and reduce the risk of large yield losses. The benefits of scientific irrigation scheduling (Stegman, 1986; Steele et al., 1994; Steele et al., 2000) and corn yield response to limited irrigation have been studied (Klocke et al., 2004; Klocke et al., 2007; Lamm et al., 2009). English et al. (2002) calls for "more detailed models of the relationships between applied water, crop production, and irrigation efficiency." Recent advances in technology have created an opportunity for software to transform this wealth of information into management decisions for producers. However, specific deficit strategies have not been developed for use with center pivot management software.

South Dakota State University (SDSU) Management Software (Oswald et al., 2005; Oswald, 2006) was originally designed as an on-farm decision support system, capable of fully automating center pivot irrigation by simulating soil water content in an irrigated field. Irrigation would be initiated when the soil water content dipped below a predetermined threshold. Inputs included crop type, soil water holding capacity (assuming no variation in soil type across the field), pumping rate, and weather data. The soil water content in the root zone was calculated daily based on rainfall, irrigation, evapotranspiration (*ET*), drainage/runoff, and the previous day's soil water content. Soil infiltration rates were not considered. Daily weather data consisted of rainfall, temperature, solar radiation, relative humidity, and wind speed. For real-time irrigation scheduling, soil water content would be checked with soil water sensors. As a model, long-term simulations of crop water use were

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performed with historical weather records (Oswald et al., 2005; Oswald, 2006). The scheduling software was able to maintain soil water levels above the minimum allowable balance when the system capacity was adequate for crop water needs.

Oswald (2006) also noted that "research is needed to document the impact of stress events upon predicted crop production." SDSU Management Software was designed for maximum yield production, without options for limited water scenarios. In order to develop optimum deficit irrigation strategies to be used in the software, a reliable yield model was needed for evaluating potential irrigation strategies.

The Decision Support System for Agrotechnology Transfer (DSSAT) series of crop models has been used to estimate yields based on output data from the SDSU Management Software. While DSSAT (2005) did include a water stress coefficient, it used a solar-driven growth engine and was unable to adequately account for crop water stress (Heeren, 2008). Optimal crop growth is limited by solar radiation, but a water-driven growth engine is more appropriate for modeling water limited conditions (Steduto et al., 2006).

Relating carbon assimilation directly to water use, many have developed relationships between crop yield and *ET* which account for yield reductions from crop stress during each growth stage. For example, FAO 33 (Doorenbos and Kassam, 1979) proposed that reduction in yield can be related to the reduction in *ET* by a stage-dependent coefficient. Payero et al. (2005) discussed two approaches to modeling crop yield based on water use, one accounting for the effects of stress timing, and the other relating yield directly to seasonal *ET* or transpiration (*T*). Showing linear yield-*T* and yield-*ET* relationships for soybeans, they noted that seasonal *ET* is affected most by soil water stress on days when the potential *ET* is high, "which could explain some of the effects of stress timing" resulting in stage-dependent yield models (e.g. Doorenbos and Kassam, 1979). Payero et al. (2006) showed similar results with linear yield-*ET* relationships for corn.

Hanks (1974), building on the work of de Wit (1958), suggested that the yield ratio (actual yield/potential yield) is directly proportional to the transpiration ratio (actual seasonal *T*/potential seasonal *T*). This correlation is expected since the rates of both *T* and carbon assimilation are directly impacted by the opening and closing of plant stomata. Monteith (1986) discussed the physics of gas exchange between the leaf and the atmosphere, and proposed that carbon assimilation per unit *T* is proportional to the ratio of the carbon concentration gradient to the vapor pressure gradient across the stomata. Accounting for the large daily changes in the vapor pressure gradient can improve yield prediction based on *T*. Several scientists have sought to account for changes in the evaporative demand of the atmosphere by correlating biomass accumulation to a normalized *T* instead of *T* (Bierhuizen and Slatyer, 1965; Feddes, 1985; Monteith, 1986; Keller, 2005; Steduto et al., 2007). Steduto et al. (2007) preferred normalizing *T* with reference *ET* on a daily basis, with the normalized *T* being proportional to biomass accumulation when neglecting changes in the carbon concentration gradient. They developed an equation which predicts seasonal biomass based on a normalized biomass water productivity coefficient, which is constant for a given crop:

$$WP_b{}^* = \frac{Biomass}{T^*} = \frac{Biomass}{\sum \frac{T}{ET_r}} \tag{1}$$

where $WP_b{}^*$ is the normalized biomass water productivity, *Biomass* is the seasonal above ground biomass (kg ha^{-1}), T^* is the normalized seasonal transpiration, T is the daily transpiration (mm d^{-1}), and ET_r is the daily reference evapotranspiration (mm d^{-1}). While the biomass water productivity (WP_b) is the biomass produced per unit of water transpired, the $WP_b{}^*$ is the biomass produced per unit of normalized *T*. This approach was selected for use in the FAO model *AquaCrop* (Steduto et al., 2006; Steduto et al., 2009).

This theoretical basis for yield prediction had not previously been utilized in the SDSU Management Software. The objectives of this research were 1) to develop a simple yield model for the SDSU Management Software, 2) to develop a method for evaluating deficit irrigation strategies with the SDSU Management Software, and 3) to recommend deficit and full irrigation strategies for various locations, soil types, and system capacities.

Methods

In order to predict crop yield under deficit irrigation, the SDSU Management Software (Oswald et al., 2005; Oswald, 2006) was updated with a new yield model and ET partitioning. Several deficit irrigation strategies were evaluated with historical simulations predicting yield ratio. Both development and simulations were performed in LabVIEW (National Instruments, Austin, Tex.), a graphical programming environment.

Model Development: Yield Ratio

Yield calculations were based on the idea of biomass water productivity, which is biomass produced per unit of water consumed (Steduto et al., 2007). The Steduto et al. (2007) model (eq. 1) was modified to account for variation in the carbon concentration gradient (eq. 2), consistent with Monteith (1986). The carbon concentration gradient was assumed to be proportional to the atmospheric carbon dioxide concentration (CO_2). Following this approach, T is normalized with both the reference ET and CO_2 on a daily basis and is related to seasonal biomass.

$$WP_b{}^{**} = \frac{Biomass}{T^{**}} = \frac{Biomass}{\sum T \frac{CO_2}{ET_r}} \tag{2}$$

where $WP_b{}^{**}$ is the biomass water productivity normalized with both ET_r and CO_2, and T^{**} is the seasonal transpiration normalized with both ET_r and CO_2. The harvest index (*HI*) is the ratio of the grain portion of the biomass to the total above ground biomass, resulting in an equation for grain yield:

$$Y = (HI)(WP_b{}^{**})(T^{**}) \tag{3}$$

where Y is the grain yield (kg ha^{-1}) and HI is the harvest index. The WP_b** is a constant for a particular crop. The HI was also assumed to be constant, based on the work of Howell (1990) who showed that HI does not vary significantly with total biomass except for very low levels of annual biomass.

In order to minimize the number of inputs required, the yield ratio was selected to evaluate the relative impacts of deficit irrigation. The daily CO_2 within a season can be treated as constant, since annual variation in CO_2 is approximately 1% to 2% (Keeling et al., 1976). While yields would be expected to increase over several years due to significant increases in CO_2, the effects of increasing CO_2 on actual yield and potential yield are the same and, thus, cancel each other. In this research, potential yield is defined as the yield that occurs when T is never restricted due to soil water stress throughout the growing season. In contrast to a traditional transpiration ratio of T/T_p, the yield ratio defined in terms of equation 3 is equivalent to the normalized transpiration ratio:

$$\frac{Y}{Y_p} = \frac{T^{**}}{T_p^{**}} = \frac{\sum T \frac{CO_2}{ET_r}}{\sum T_p \frac{CO_2}{ET_r}} = \frac{CO_2 \sum \frac{T}{ET_r}}{CO_2 \sum \frac{T_p}{ET_r}} = \frac{\sum \frac{T}{ET_r}}{\sum \frac{T_p}{ET_r}} \quad (4)$$

where Y_p is the potential grain yield (kg ha^{-1}), T_p** is the potential normalized seasonal transpiration, and T_p is the daily potential transpiration (mm d^{-1}).

Since the yield model required T data, the SDSU Management Software was updated with a dual crop coefficient procedure (Heeren, 2008). The reference ET was the tall reference Penman-Monteith, calculated according to the ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 2005). Following FAO 56 (Allen et al., 1998) and Allen et al. (2007), ET was partitioned into evaporation and T:

$$ET_c = (K_s K_{cb} + K_e) ET_r \quad (5)$$

where ET_c is the daily actual crop ET (mm d^{-1}), K_s is the soil water stress coefficient, K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient, and ET_r is the daily reference ET (mm d^{-1}). The K_{cb}, which determines the daily potential T, depends on the crop growth stage and the reference ET equation used. Evaporation is estimated with K_e, which is calculated according to the AW of the topsoil (a separate soil water balance is maintained for the layer of soil that can lose water to evaporation) and the percent of the ground exposed to sunlight. When ET partitioning coefficients are analyzed across a growing season (fig. 1), irrigation and rainfall events are apparent by sharp increases in evaporation. Soil water stress is indicated from dips below the trend in the $K_s K_{cb}$ (transpiration) curve. Following FAO 56 (Allen et al. 1998), K_s is a water stress coefficient accounting for the reduction in transpiration due to soil water content. Consistent with the observations of Denmead and Shaw (1962), reductions in T were dependent on both soil water content and meteorological conditions. The K_s is unity after a large rain or irrigation event and subsequently constrains T as the soil dries out:

$$K_s = \min\left(\frac{AW/100}{1-p}, 1\right) \quad (6)$$

$$AW = \frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}} 100\% \quad (7)$$

where p is the fraction of water in the root zone available before moisture stress occurs (mm mm^{-1}), AW is the available water (%), θ is the actual volumetric water content (m^3 m^{-3}), θ_{FC} is the volumetric water content at field capacity (m^3 m^{-3}), and θ_{WP} is the volumetric water content at the wilting point (m^3 m^{-3}). As soil dries, p reflects the point at which water stress starts occurring. Since water movement from the soil to the roots is more likely to be a limiting factor when the evaporative demand of the atmosphere is high, p is dependent on the T_p for that day:

$$p = 0.55 - 0.04(T_p - 5), 0.1 \le p \le 0.8 \quad (8)$$

For example, on a hot, dry day when T_p is 9 mm, K_s becomes less than one if AW falls below 61%. This concept is consistent with Stegman et al. (1976), who observed that crop water stress may be inevitable when the temperature is above 37.8°C, even if soil water levels are at field capacity.

Based on equations 4 and 5, T and T_p can be expanded, resulting in a simple yield model:

$$\frac{Y}{Y_p} = \frac{\sum \frac{T}{ET_r}}{\sum \frac{T_p}{ET_r}} = \frac{\sum \frac{K_s K_{cb} ET_r}{ET_r}}{\sum \frac{K_{cb} ET_r}{ET_r}} = \frac{\sum K_s K_{cb}}{\sum K_{cb}} \quad (9)$$

This equation for yield ratio only requires daily values of the basal crop coefficient and water stress coefficient, allowing the yield ratio to be calculated at the end of the simulated growing season. This yield model is not crop specific and may be applicable to other crops as long as the ET routines are adapted accordingly and the constant HI assumption applies.

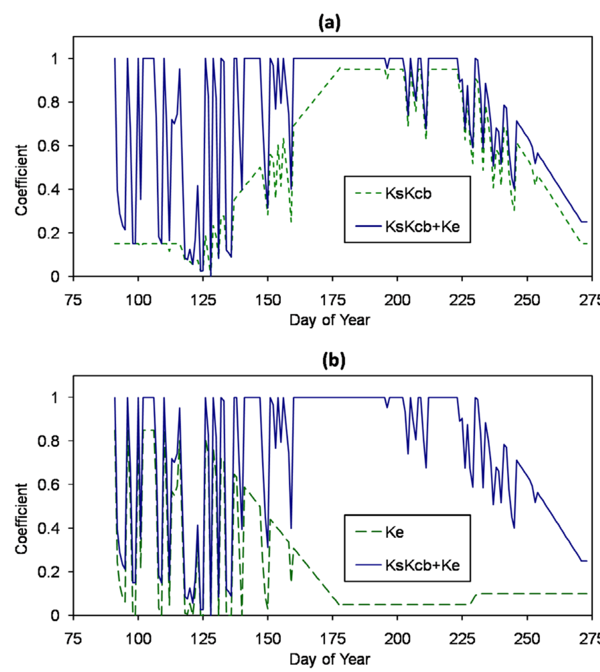

Figure 1. Example of coefficients for ET partitioning throughout a growing season, comparing T to ET (a) and E to ET (b).

The yield ratio is essentially the average daily water stress coefficient, weighted by K_{cb}. In two ways, this model accounts for the mid-season increase in crop sensitivity that previous research has observed. First, water stress when K_{cb} is high (mid-season) will have a larger effect on yield than early or late season stress. Also, K_s depends on T_p, so that a higher evaporative demand (often mid-season) results in a greater reduction in K_s for a given soil water level.

A pictorial example of equation 9 is shown in figure 2. Conceptually, each graph is integrated to obtain the seasonal K_{cb} and seasonal $K_s K_{cb}$, with the quotient being the relative yield (0.94 in this case). Practically, the SDSU Management Software determines the cumulative $K_s K_{cb}$ and K_{cb} at the end of each day and calculates the yield ratio at the end of the season.

Model Evaluation with Field Data

The yield model was evaluated against field data (Klocke et al., 2007) from corn under deficit irrigation from 1992 to 1998 at the West Central Research and Extension Center of the University of Nebraska-Lincoln at North Platte, Nebraska. The predominant soil texture was Cozad silt loam (fluventic Haplustoll) with pH of 7.5. The soil profile (from 0 to 3 m) had a field capacity of 0.32 $m^3 m^{-3}$ and a permanent wilting point of 0.15 $m^3 m^{-3}$, resulting in a plant-available soil water holding capacity of 0.17 $m^3 m^{-3}$. No-till cropping practices and non-limiting fertility and pest management were used. Pre-emergence and post-emergence herbicides were applied as needed.

A solid set irrigation system was installed with sprinklers on a 12- × 12-m square grid with a wetted radius of 12 m. The nominal plot area was 12 × 12 m, surrounded by another 12 m of buffer between plots that served as a border to separate plots with different water treatments. Corn yields were measured from randomly selected adjacent two rows, each 6 m long. Irrigation treatments included dryland, limited irrigation, and full irrigation. An annual water allocation was restricted to 150 mm for the limited irrigation treatments, which were scheduled to favor applications during critical growth stages for crop development. For corn, irrigation was reduced or withheld during the vegetative period and concentrated on the reproduction and grain fill stages. Three crop rotations were used; a detailed presentation is given in Klocke et al. (2007). Yield ratio for the field data was determined by dividing the yield for each plot by the maximum yield. It is possible that the maximum yield in the field data was lower than the potential yield as defined above. North Platte has a climate similar to Akron, Colorado, and St. John, Kansas, which failed to produce a yield ratio of one in the simulation results (fig. 5). It is acknowledged that this a source of potential error in the analysis that would result in the observed yield ratio being higher than the theoretical yield ratio.

The 1995 season, which was the driest year in the data set (1992-1998), was selected as an appropriate test for the yield model. Limited rainfall resulted in a season that showed large differences in yield between the full and limited irrigation treatments. Daily weather data was downloaded from the High Plains Regional Climate Center (2007). The SDSU Management Software was used to simulate *ET*, soil water content, and yield ratio. While the software is capable of automatically scheduling irrigation events, irrigation dates and amounts were manually entered into the model according to actual irrigation applications during the field study (Klocke et al., 2007). In this way, the soil water balance and yield model routines could be evaluated by comparing simulated and measured yield data.

Yield ratio for each treatment was plotted against the amount of irrigation water used (fig. 3) for both field data and model simulations. Each point represents a particular combination of irrigation strategy and crop rotation and is an average of four repetitions. The standard error among the replications was calculated. The results show a good correlation between model and field data. For the limited irrigation treatment, the yield model predicted an average yield ratio of 0.56 while the field data had an average yield ratio of 0.63. For the full irrigation treatment, average yield ratios for model and field data were 0.83 and 0.84, respectively.

This analysis indicates that the yield model accounts for yield reductions due to water stress from soil water deficits. The correlation in yield data also indicates that the SDSU Management Software effectively simulated *ET* and soil water content which have a large impact on the yield ratio calculations.

Historical Simulations to Evaluate Strategies

In order to develop and evaluate deficit irrigation strategies, the SDSU Management Software was used to simulate center pivot irrigation and corn yield with historical

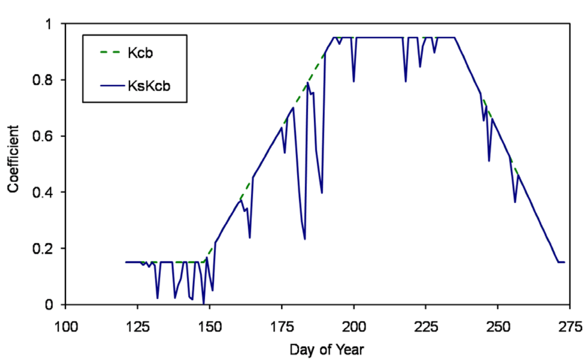

Figure 2. Example of the transpiration coefficients needed for the yield model. The estimated yield ratio is equal to the ratio of the area under the solid line (correlating to actual transpiration) to the area under the dashed line (correlating to potential transpiration).

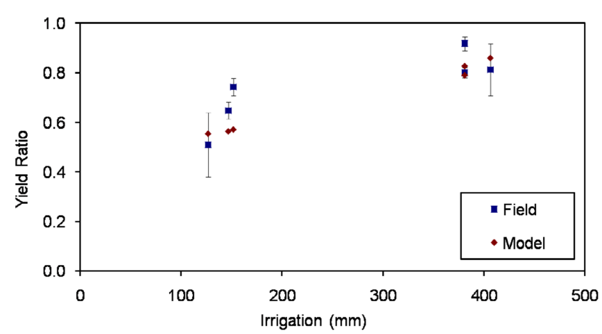

Figure 3. Comparison between field data and SDSU Management Software. The cluster on the left is the deficit irrigation treatment, and the cluster on the right is the full irrigation treatment. Each point is for a specific crop rotation. Error bars show the standard error among the replications for field data.

weather data. Simulations were performed on seven locations (each with 16 to 24 years of historical weather data) across the Great Plains, with 30 irrigation strategies, three soil types, and three pumping rates. Loops were used in LabVIEW to cycle annual simulations through all treatments and years. A total of 40,000 simulations were performed. Output files included data for *ET*, soil water levels, irrigation amounts, and yield ratio.

The SDSU Management Software was set up to simulate a center pivot irrigator with an effective length of 418 m (1370 ft), covering 55 ha (135 acres). Irrigation application efficiency was assumed to be 90%. When an irrigation event was triggered for a given day, the irrigator would continue until it reached a portion of the field that did not need irrigation or until it had traveled the maximum distance possible in 24 h based on effective application depth and pumping rate. Pumping rates included 38, 51, and 63 L/s (600, 800, and 1000 GPM).

Seven locations were selected across the Great Plains. For the historical simulations, weather data, latitude to calculate clear sky solar radiation, elevation to calculate mean air pressure, and growing season length were the only variables that depended on location. Weather data were downloaded from the High Plains Regional Climate Center (2007). Average annual precipitation ranged from less than 510 cm (20 in.) in Colorado and western South Dakota to more than 760 cm (30 in.) in Missouri. Climagraphs were used to compare average monthly reference *ET* (ET_r) to rainfall during the growing season for each location (fig. 4). While the precipitation trend follows ET_r for Rock Port, Missouri, peak rainfall is reached two months before peak monthly ET_r in Nisland, South Dakota, and Akron, Colorado. Climate trends can indicate the potential for mid- to late-season water stress for a given location.

Three soil types were selected to represent a range of soils and were simulated at all locations. Soil types included available water holding capacity (*AWHC*) values of 0.08, 0.13, and 0.17 m m^{-1} (1, 1.5, and 2 in. ft^{-1}), with AWHC defined as the difference between θ_{FC} and θ_{WP}. The rooting depth was set at 305 mm for the initial portion of the season, and then proceeded linearly to 914 mm from 15% to 46% maturity (PM), which is the ratio of days after planting to total days in the growing season. The rooting depth then remained at 914 mm for PM greater than 46%. When the root zone was deeper than it had been the previous day, the soil newly available for water uptake was assumed to have the same AW as the rest of the root zone.

Irrigation strategies were used to determine irrigation timing and amounts. A method was needed to numerically describe an irrigation strategy so that strategies could be changed and modeled easily. An irrigation strategy was defined by the target minimum available water (*MAW*) as it varies throughout the season. This concept is similar to the maximum allowable depletion (*MAD*), with *MAW* = 100 – *MAD*. Irrigation events were triggered when the soil in the sector directly in front of the center pivot irrigator dried to the *MAW*. The effective irrigation depth was based on the difference between the *MAW* and a maximum *AW*, which was

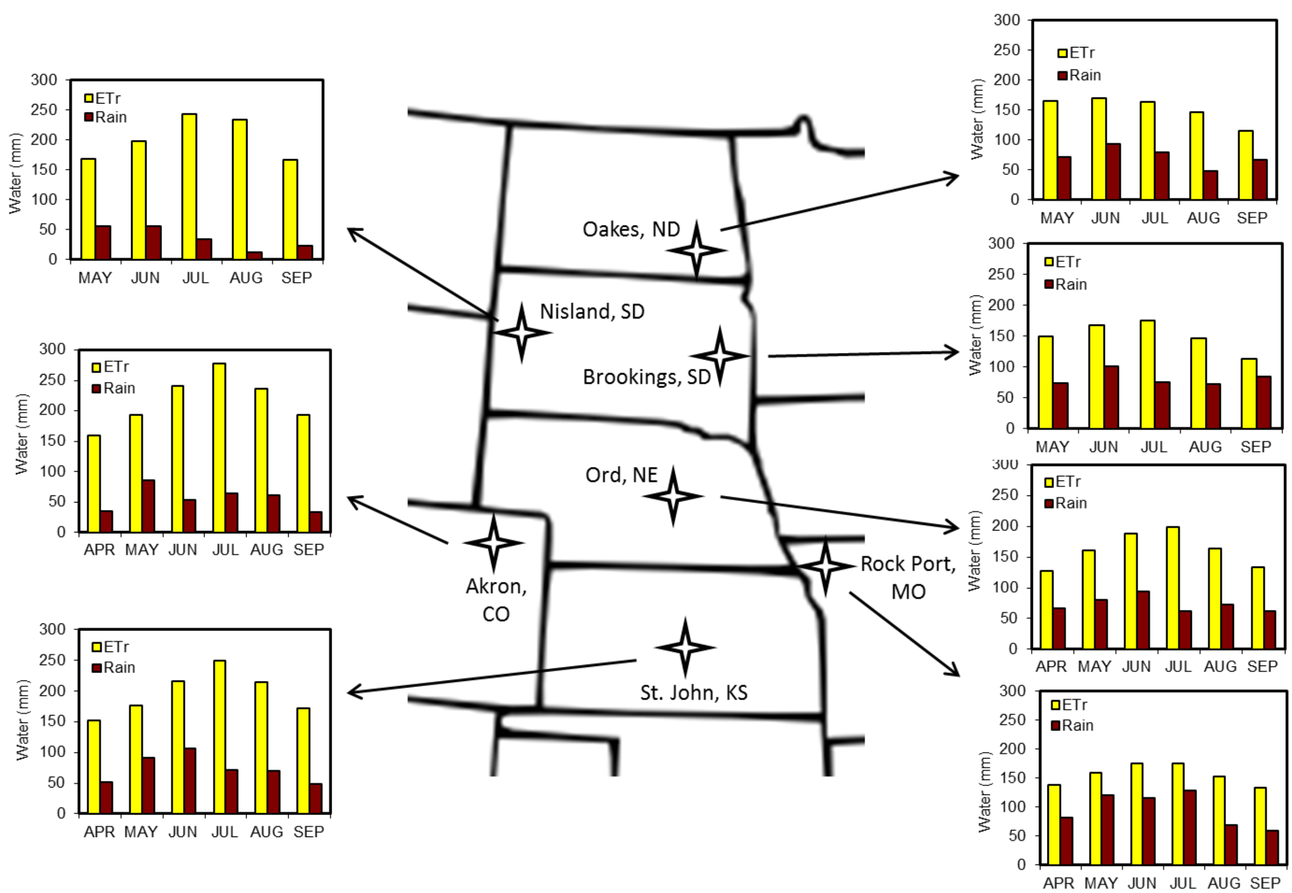

Figure 4. Site locations and associated climagraphs showing average monthly reference ET$_r$ and rainfall (mm).

60%, 80%, and 50% for early, middle, and late season, respectively. The purpose of the maximum *AW* was to increase the likelihood of rainfall being retained in the soil profile. The effective irrigation depth was also constrained by a maximum of 32 mm and a minimum of 5, 13, and 5 mm for early, middle, and late season, respectively. An application depth of 5 mm may be small compared to typical center pivot irrigation practice. Simulation results indicated that effective irrigation amounts ranged from 5 to 32 mm (0.2 to 1.25 in.) with approximately 65% to 80% of irrigation events having an effective application depth greater than 19 mm. Maximum area covered by the irrigator for a given day was determined by effective application depth, irrigation efficiency, and pumping rate.

Thirty strategies were defined for the simulations. These were inputs for the SDSU Management Software, which ran center pivot and yield simulations for each strategy. The general shape of most of the strategies specified higher *MAW* levels mid-season and lower *MAW* levels early and late-season. This is based on the observed effects of stress timing, showing that corn is more sensitive to water stress during flowering than the vegetative and yield formation phases of development (Doorenbos and Kassam, 1979).

Irrigation strategies were labeled by the *MAW* values for early (MAW_1), middle (MAW_2), and late (MAW_3) season (fig. 5). Each strategy was also defined by timing parameters which specified the *PM* at the end (PM_1) of MAW_1, the beginning (PM_2) and end (PM_3) of MAW_2, and the beginning (PM_4) of MAW_3 (table 1). Many strategies have similar timing parameters, although “30-60-30 extended” has a notably longer peak (MAW_2) than most. Based on the parameters for a strategy, the *MAW* for any point in the season can be determined.

The center pivot SDSU Management Software divided a circular field into 60 sections, each a 6° sector with its own water balance. While soil type was assumed to be homogenous within a field, the amount and timing of irrigation applications varied throughout the field due to the logistics of center pivot operation. To account for this spatial variability, yield was calculated for three equidistant sectors within the field and the results were averaged for each simulation. Initial *AW* was set to 80% at the beginning of each season for each location. (This assumption was compared to a 20% initial *AW* at a dry site: while seasonal irrigation changed slightly, the shape of the yield-irrigation graph remained the same.)

Results

Water Relationships

For each location, the yield ratio was generally proportional to *T* (fig. 6). Crops at sites with greater evaporative demand had a smaller increase in yield for each unit increase in *T*.

Yield ratio was also plotted against seasonal irrigation values in order to evaluate irrigation strategies. Figure 7 shows the summary of the results, with all 30 strategies represented for each location. At some sites, a yield ratio of one was not attained. In hot and dry climates, it is very difficult to maintain K_S equal to one throughout the growing season. According to the definition of potential yield used in this research, actual yield is equal to potential yield only if *T* is never reduced due to soil water stress.

Sites with lower rainfall and higher *ET* demand showed greater yield loss for deficit irrigation strategies and required more water for high yields. The yield-irrigation relationship was relatively linear for most locations until maximum yield was approached. Once on the plateau, the crop producer would experience negligible returns for additional irrigation water. When irrigations are effectively scheduled and water losses due to untimely rainfall remain small, diminishing returns are not experienced until the maximum yield ratio is reached, after which the diminishing return is actually no return.

The differences between the yield-*T* (fig. 6) and yield-irrigation (fig. 7) relationships were due to evaporation, rainfall, and water losses. Losses, which included runoff and deep percolation, generally increased for strategies that applied more irrigation.

Recommended Strategies

The yield-irrigation relationship is the most relevant of the yield-water relationships for evaluating irrigation strategies. An example yield-irrigation graph is shown in figure 8, with strategies of interest labeled.

The distributions of the 30 irrigation strategies (in relation to each other) on the yield-irrigation plot in figure 8 were generally representative of plots for all locations, soil types,

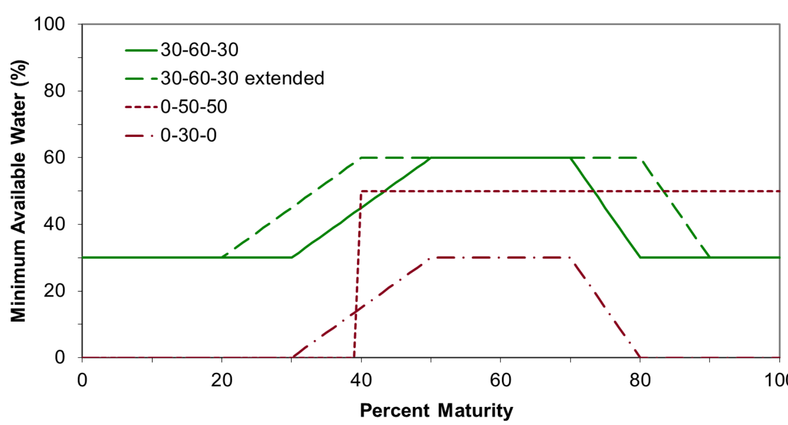

Figure 5. Selected irrigation strategies, which are defined by the target minimum available water for early, middle, and late season. Most of the thirty strategies used required higher soil water levels during flowering. The “30-60-30 extended” strategy is the same as “30-60-30” except with an extended peak during mid-season.

Table 1. Irrigation strategies used in historical simulations.

Strategy	PM_1	PM_2	PM_3	PM_4	MAW_1	MAW_2	MAW_3	Description
70-70-70	30	50	70	80	70	70	70	Upper limit
50-50-50	40	40	60	60	50	50	50	Traditional
50-50-0	40	40	60	60	50	50	0	Stop mid-season
50-0-0	40	40	60	60	50	0	0	Stop mid-season
40-70-40	30	50	70	80	40	70	40	
40-60-40	30	50	70	80	40	60	40	
30-70-30	30	50	70	80	30	70	30	
30-60-30	30	50	70	80	30	60	30	Original in software
30-60-30 alt1	30	50	60	70	30	60	30	
30-60-30 alt2	30	40	70	80	30	60	30	
30-60-30 alt3	30	50	70	90	30	60	30	
30-60-30 alt4	20	50	70	80	30	60	30	
30-60-30 extended	20	40	80	90	30	60	30	Extended peak
30-60-15	30	50	70	80	30	60	15	
30-50-0	30	50	70	80	30	50	0	
30-30-30	40	60	60	70	30	30	30	
15-50-15	30	50	70	80	15	50	15	
15-50-0	30	50	70	80	15	50	0	
15-30-15	30	50	70	80	15	30	15	
15-30-15 alt1	40	60	70	80	15	30	15	
15-30-15 alt2	30	50	60	70	15	30	15	
15-30-0	30	50	70	80	15	30	0	
15-15-15	40	60	60	70	15	15	15	
10-15-0	30	50	70	80	10	15	0	
0-50-50	40	40	60	60	0	50	50	Late start
0-50-0	40	60	70	80	0	50	0	
0-30-15	30	50	70	80	0	30	15	Late start
0-30-0	30	50	70	80	0	30	0	
0-15-0	30	50	70	80	0	15	0	
0-0-0	30	50	70	80	0	0	0	Lower limit

and pumping rates. The 0-0-0 strategy, which initiated irrigation only when the wilting point was reached, provided a lower bound on the data set. The 70-70-70 strategy, providing an upper limit on the data set, produced a minimal increase in yield (compared to similar strategies) for the large amount of applied water it required. Seasonal losses to surface runoff and/or drainage increased with increasing irrigation after 250 to 450 mm (depending on the location) of seasonal irrigation. The 30-60-30 strategy was the original strategy in the SDSU Management Software. It was found that, depending on location, a pumping rate of 51 or 63 L s^{-1} was required to adequately elevate *AW* levels from 30% in the early season to 60% when the crop was most susceptible to yield loss.

The historical strategy of 50-50-50 resulted in high yields, but it also consistently used more water than other strategies with similar yields. The 50-0-0 and 50-50-0 strategies, representing situations where available irrigation water was used up before the end of the season, consistently performed poorly. This indicates the benefit of good irrigation

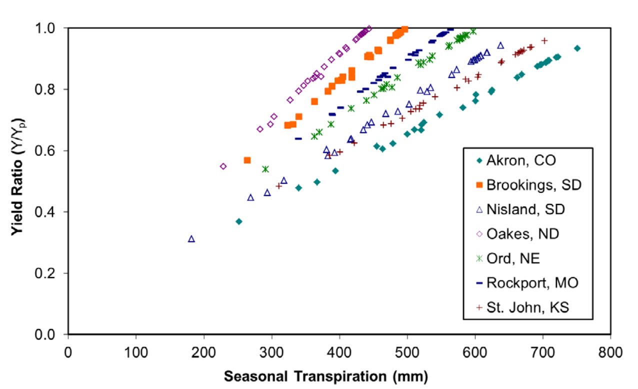

Figure 6. Yield-transpiration relationship for each site. Each point represents an irrigation strategy. Data are averaged across all AWHCs, pumping rates, and years.

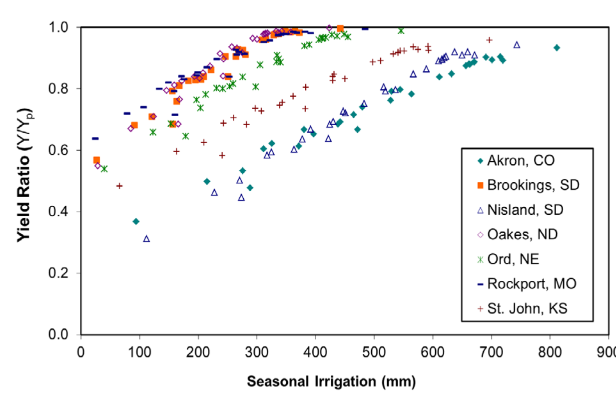

Figure 7. Yield-irrigation relationship for each site. All AWHCs, pumping rates, and years. Net seasonal irrigation is used, based on a 90% application efficiency.

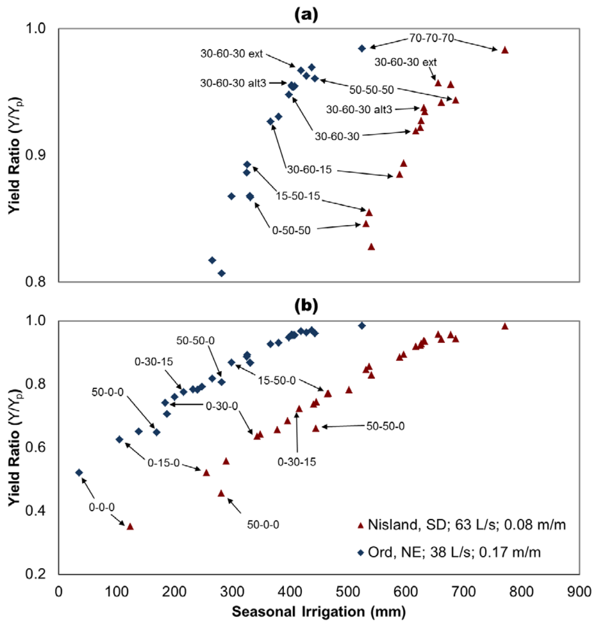

Figure 8. Example of yield-irrigation relationships for two locations, pumping rates, and soil types with selected strategies labeled, showing an inset (a) as well as all thirty strategies (b).

management, resulting in higher yields for a given supply of water.

Irrigation water use efficiency (*IWUE*) is a concept that compares crop production to water used and has been defined in numerous ways. In this research, *IWUE* was defined as relative grain yield per unit of irrigation. The best irrigation strategies were considered to be the ones that resulted in a high *IWUE*; that is, they produced a relatively large yield for a given amount of irrigation. On a yield-irrigation graph, high *IWUE* strategies were the points with a higher yield ratio than other points with the same or larger amount of irrigation. The high *IWUE* strategies indicated by figure 8 performed well across all locations, soil types, and pumping rates.

The 0-50-50 and 0-30-15 strategies were found to be high *IWUE* strategies. This indicated that delaying irrigation early in the season (unless wilting point is reached), a deficit strategy that is relatively easy to implement, results in good water use efficiency. Similarly, a late irrigation strategy, delaying irrigation until two weeks before tassel emergence unless soil water depletion reached 70%, has been shown to reduce irrigation water use by 15% with minimal impact on yield (Melvin and Payero, 2007) and to increase *IWUE* by 21% (Klocke et al., 2004) compared to a 50-50-50 strategy (i.e. best management practice) for corn field sites in Nebraska.

Of the high *IWUE* strategies, four were selected for recommendation that covered a range of deficit irrigation conditions as well as full irrigation. Yield and irrigation data for these strategies are shown in table 2. Recommended deficit irrigation strategies are 15-50-0, 0-30-0, and 0-15-0 for minimal, moderate, and severe water restrictions. The recommended maximum yield strategy is 30-60-30 extended for Akron, Colorado; Nisland, South Dakota; Ord, Nebraska; and St. John, Kansas. For Brookings, South Dakota; Oakes, North Dakota; and Rock Port, Missouri, where the 30-60-30 extended provided little yield benefit for the extra water required, the recommended maximum yield strategy is 30-60-30.

Data from table 2 (or fig. 7) can be used for long-term planning. For example, a corn producer in Nisland, South Dakota, with a limited water supply could expect a greater total yield by applying 320 mm of irrigation water on 55 ha compared to applying 640 mm on half of his field, leaving the rest fallow. Planting one half of the field to a dryland crop, however, could change the comparison. In fact, these data could be used to support economic analyses for a variety of agricultural management scenarios. Simulation data from the recommended maximum yield strategies were also compared specifically to results from a traditional irrigation strategy (50-50-50). Water savings and changes in relative yield are reported in table 3. These results are consistent with Steele et al. (1994) who found that, based on a field study of corn near Oakes, North Dakota, more advanced irrigation scheduling could improve yield and reduce irrigation water use by 40% compared to a 60-60-60 irrigation strategy (i.e. 40% allowable depletion). Also, Klocke et al. (2004) was able to conserve 5% of irrigation water use and maintain crop yields using best management practices compared to existing farm strategies on three field sites in southwest Nebraska.

Table 2. Yield ratio and seasonal irrigation (mm) (in parentheses) for recommended irrigation strategies.[a]

Water Restriction	Strategy	Akron, Colo.	Brookings, S. Dak.	Nisland, S. Dak.	Oakes, N. Dak.	Ord, Nebr.	Rock Port, Mo.	St. John, Kans.
None	30-60-30[b]	0.90	0.98	0.92	0.98	0.98	0.98	0.94
		(691)	(328)	(637)	(311)	(428)	(336)	(567)
Minimal	15-50-0	0.74	0.91	0.73	0.91	0.88	0.90	0.81
		(480)	(246)	(447)	(238)	(305)	(231)	(383)
Moderate	0-30-0	0.61	0.79	0.58	0.79	0.76	0.80	0.69
		(312)	(156)	(318)	(146)	(197)	(134)	(244)
Severe	0-15-0	0.50	0.68	0.46	0.67	0.66	0.72	0.60
		(215)	(91)	(228)	(86)	(123)	(79)	(163)

[a] Data are averaged over all soil types, pumping rates, and years.
[b] The maximum yield strategy, which is 30-60-30 for Brookings, S. Dak.; Oakes, N. Dak.; and Rock Port, Mo., and 30-60-30 extended for Akron, Colo.; Nisland, S. Dak.; Ord, Nebr.; and St. John, Kans.

Table 3. Benefit of recommended maximum yield strategies. All AWHCs, pumping rates, and years.

		Akron, Colo.	Brookings, S. Dak.	Nisland, S. Dak.	Oakes, N. Dak.	Ord, Nebr.	Rock Port, Mo.	St. John, Kans.
I (mm)	Traditional	720	372	671	359	456	392	593
	Recommended	691	328	637	311	428	336	567
	Change	-29	-44	-34	-47	-27	-56	-26
	Percent reduction	4	12	5	13	6	14	4
Y / Y_p	Traditional	0.89	0.98	0.91	0.98	0.97	0.98	0.92
	Recommended	0.90	0.98	0.92	0.98	0.98	0.97	0.94
	Change	0.01	0.00	0.01	0.00	0.01	-0.01	0.02

Pumping Rate and Soil Type

Pumping rate and soil type had a negligible effect on which strategies performed best (high *IWUE*). The same strategies are recommended for all pumping rates and soil types. Yields were only minimally affected by *AWHC* when pumping rates were sufficient for a particular strategy and location. Pumping rate did have a large impact on yield in some cases. While the general yield-irrigation relationship was not significantly affected by pumping rate, a low pumping rate limited the irrigation that could be applied and the corresponding yield ratio was reduced. All sites showed at least a slight reduction in yield when the pumping rate was limited to 38 L s^{-1}. Akron, Colorado; Nisland, South Dakota; and St. John, Kansas, showed substantial yield losses with a pumping rate of 38 L s^{-1}, and small losses with 51 L s^{-1} compared to 63 L s^{-1}. It is not surprising that the sites with the greatest middle- and late-season difference between monthly ET_r and precipitation (fig. 4) showed the largest yield reductions from limited pumping rates.

Annual Variation

Each irrigation strategy resulted in a different yield ratio and irrigation use for each year. Figure 9 shows error bars (standard deviation across all years) on a yield-irrigation plot for both an arid and a sub-humid climate. There was more annual variation in irrigation use for strategies with higher water use. However, annual variation in yield was highest for strategies with the lowest irrigation amount. This information is valuable for risk management. For example, a deficit irrigation strategy may be economically beneficial on average, but the producer would have to be willing to accept greater variability in yield from year to year.

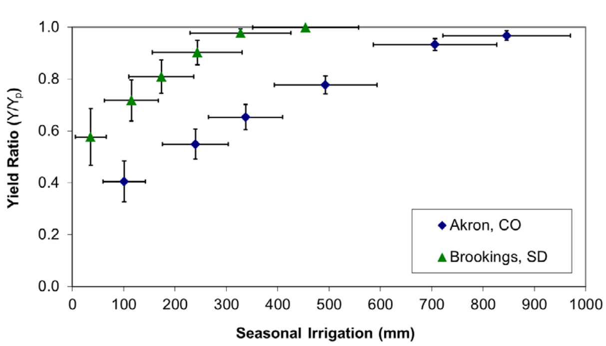

Figure 9. Example of standard deviation (for annual variation) shown on a yield-irrigation plot. All years, 0.08 m m^{-1} AWHC, 63-L s^{-1} pumping rate, 0-0-0, 70-70-70, and recommended strategies.

Conclusions

A simple yield model was developed to estimate yield ratio based on a normalized transpiration ratio. Model results compared favorably to field data from deficit irrigation research on corn, indicating that the yield model accounted for yield loss due to water stress. This yield model should be applicable to other crops as long as the *ET* routines are adapted accordingly and the constant harvest index assumption applies. Requiring only daily *T* data, the yield model was incorporated into SDSU Management Software.

Thirty deficit irrigation strategies were evaluated by simulating center pivot irrigation and corn yield ratio with historical weather data. The recommended maximum yield strategy for corn is 30-60-30 for Brookings, South Dakota; Oakes, North Dakota; and Rock Port, Missouri; and 30-60-30 extended for Akron, Colorado; Nisland, South Dakota; Ord, Nebraska; and St. John, Kansas. Recommended deficit irrigation strategies (for all sites) are 15-50-0 for minimal water restrictions, 0-30-0 for moderate water restrictions, and 0-15-0 for severe water restrictions. Recommended irrigation strategies did not depend on soil type or pumping rate.

Variability in yield from year to year is greatest for strategies that use the least water. Pumping rate had a negligible effect on the general yield-irrigation relationship, but a pumping rate of 37.9 L s^{-1} did substantially limit maximum yields in Akron, Colorado; Nisland, South Dakota; and St. John, Kansas.

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